CHARACTERISATION OF IONOSPHERIC TEC VARIATIONS OVER THE EQUATORIAL AND POLAR REGIONS DURING SOLAR CYCLE 24

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For my beloved father and mother

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ABSTRACT

The TEC variations in the equatorial and polar region are known to be high compared to the mid latitude region. Investigation on ionospheric TEC at individual regions has been carried out by many studies but the investigation between these regions simultaneously is still lacking. TEC values from Libreville (*NKLG*), Gabon (0.4162°N, 9.4673°E), and Ny-Alesund (*NYA1*), Norway (78.9235°N, 11.9099°E), each representing equatorial and polar station, respectively, are obtained for the year 2009, 2011, and 2013 to observe their TEC behaviors. The diurnal and seasonal variations of TEC and geomagnetic effects on TEC variations are analyzed for both stations. Besides, the rate of TEC change, *K*, is obtained to relate the TEC variations between these locations simultaneously. The pseudo-TEC measurement measured by dual frequency GPS which can be obtained from IGS server, is used to calculate vertical TEC. The ranges of maximum diurnal TEC at *NKLG* and *NYA1* station is 23-114 TECU and 8-55 TECU, respectively. The seasonal TEC peak at both stations encountered the highest TEC at equinoctial months and the lowest value at solstitial months. However, in 2009, the seasonal TEC showed the highest and lowest TEC peak, both at equinoctial months at *NYA1* station. During geomagnetic days, the enhancement percentages of TEC are found on 22 July 2009 and 17 March 2013 at *NKLG* station, and 22 July 2009 and 25 October 2011 at *NYA1* station. The decrement percentage of TEC observed on 25 October 2011 and 17 March 2013 at *NKLG* and *NYA1* station, respectively. The rate of TEC change shows a same definite pattern over all the years. It can be concluded that the hourly maximum TEC values at *NKLG* station fell within 0.4-1.9 times larger than that *NYA1* station. This study helps to have more understanding of the unique characteristics at the equatorial and polar ionosphere.

ABSTRAK

Variasi TEC di kawasan khatulistiwa dan kutub diketahui adalah tinggi dibandingkan di kawasan latitud tengah. Penyiasatan terhadap TEC ionosfera di kawasan individu telah banyak dijalankan oleh beberapa kajian tetapi penyiasatan antara dua kawasan ini dijalankan secara serentak adalah masih kekurangan. Nilai-nilai TEC daripada Libreville (*NKLG*), Gabon (0.4162°U, 9.4673°T), dan Ny-Alesund (*NYA1*), Norway (78.9235°U, 11.9099°T), setiap satu mewakili stesen khatulistiwa dan kutub diperolehi untuk tahun 2009, 2011, dan 2013 untuk memerhatikan perlakuan TEC. Variasi TEC harian dan bermusim, dan kesan geomagnetik terhadap variasi TEC dianalisis untuk kedua-dua stesen. Selain daripada itu, perbezaan variasi TEC, *K* dilakukan untuk menghubungkaitkan variasi TEC antara lokasi-lokasi ini secara serentak. Ukuran pseudo-TEC diukur oleh GPS dwi frekuensi digunakan bagi mengira nilai TEC menegak dimana boleh diperolehi daripada pelayar IGS. Julat maksimum harian di stesen *NKLG* dan di stesen *NYA1* masing-masing adalah 23-114 TECU, dan 8-55 TECU. Puncak TEC bermusim di kedua-dua stesen menunjukkan TEC tertinggi di bulan-bulan ekuinoks dan nilai terendah di bulan-bulan solstis. Walaubagaimanapun, pada 2009, TEC bermusim menunjukkan puncak TEC tertinggi dan terendah, kedua-duanya di bulan-bulan ekuinoks di stesen *NYA1*. Semasa hari-hari geomagnetik, peratus peningkatan TEC dijumpai pada 22 Julai 2009 dan 17 Mac 2013 di stesen *NKLG*, dan 22 Julai 2009 dan 25 Oktober 2011 di stesen *NYA1*. Penurunan peratus TEC terlihat pada 25 Oktober 2011 dan 17 Mac 2013, masing-masing di stesen *NKLG* dan *NYA1*. Nilai kadar peruabahan terhadap variasi TEC menunjukkan corak pasti sama untuk keseluruhan tahun. Ia disimpulkan bahawa nilai TEC maksimum setiap jam di stesen *NKLG* adalah 0.4-1.9 kali ganda lebih besar daripada stesen *NYA1*. Pembelajaran ini membantu untuk mempunyai lebih pemahaman terhadap ciri-ciri unik di ionosfera khatulistiwa dan kutub.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	-	Semi-major axis
B_z	-	Magnetic field of southward
	-	Satellite bias
	-	Receiver bias
D	-	The lowermost ionosphere layer
E	-	The middle ionosphere layer
E x B	-	The magnetic's field line drift
F_1	-	The first uppermost ionosphere layer
F_2	-	The second uppermost ionosphere layer
2 1	-	Squared frequency of L_1
2 2	-	Squared frequency of L_2
h	-	Height of maximum electron density
K	-	Rate of TEC changes
L_1	-	First channel of dual-frequency
L_2	-	Second channel of dual-frequency
NKLG	-	Libreville station
NYA1	-	Ny-Alesund station
n	-	Electron density
O^+	-	Oxygen ion
O/N_2	-	Oxy-Nitrogen Ratio
P_2	-	L_2 Pseudorange observable
P_1	-	L_1 Pseudorange observable
	-	Earth's radius
x,y,z	-	Coordinates of location
	-	Elevation angle
1/f	-	Flattening factor of Earth
A_E	-	Auroral Electrojet index

LIST OF SYMBOLS AND ABBREVIATIONS

ASCII	-	American Standard Code for Information Interchange
CDDIS	-	Crustal Dynamics Data Information System
CMEs	-	Coronal Mass Ejections
CODE	-	Center for Orbit Determination in Europe
DCB	-	Differential Code Bias
DST	-	Disturbance Storm Time index
EEJ	-	Equatorial Electrojet
EIA	-	Equatorial Ionization Anomaly
GPS	-	Global Positioning System
HF	-	High Frequency
IGS	-	International GNSS Service
IMF	-	Interplanetary Magnetic Field
IONEX	-	Ionosphere Exchange
IPP	-	Ionospheric Pierce Point
KP	-	Planetary-K index
LT	-	Local Time
MATLAB	-	Matrix Laboratory
MUF	-	Maximum Usable Frequency
nT	-	nanoTeslas
PCA	-	Polar Cap Absorption
PPE	-	Prompt Penetration Electric Field
PRN	-	Pseudo Random Number
RINEX	-	Receiver Independent Exchange Format
SLM	-	Single Layer Model
SSC	-	Sudden Storm Commencement
SSN	-	Sunspot Number

LIST OF SYMBOLS AND ABBREVIATIONS

STEC	-	Slant Total Electron Content
TEC	-	Total Electron Content
TCVs	-	Travelling Convection Vortices
TIDs	-	Travelling Ionospheric Disturbances
TOI	-	Tongue of Ionization
UT	-	Universal Time
VTEC	-	Vertical Total Electron Content
WGS84	-	World Geodetic System

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CHAPTER 1

INTRODUCTION

1.1 Background of study

The ionosphere is situated within the Earth's upper atmosphere, with extending height from 50 km to more than 1000 km and a dispersive medium containing a large concentration of free electrons that affect radio waves propagation (Bianchi *et al.*, 2013). Free electrons are produced by the ionization process through solar radiation. Solar radiation has a particular enough amount of energy to break down the electron bonding around the Earth's atmosphere. This ionized plasma is the first medium of the atmosphere that the Global Positioning System (GPS) signal encounters as it leaves the satellite.

GPS is emphasized in exploring ionospheric electron content on regional as well as a global basis, due to the availability of signals in all-time and all-weather condition around the globe (Zhao *et al.*, 2016). One of the largest errors in GPS positioning is attributable to the ionosphere. The ionosphere alters the apparent speed, to a lesser extent, the direction of the GPS signal. This causes an apparent delay in the signal's transit from the satellite to the receiver. The magnitude of these delays is determined by the amount of ionization along the ray path (i.e., the line integral of electron density known as the Total Electron Content (TEC)).

The ionospheric layers consist of D layer, E layer, and F layer, from the lowest to the uppermost part of the ionosphere. Solar radiation is stronger at the higher altitudes but there is less interaction with gaseous atoms hence the ionization is scattered. It explains the temporal and spatial feature of the ionosphere (Kelley, 2015).

The ionosphere can be categorized into three regions based on the latitude; low, middle, and high. The low latitude region is within about 0° to ~23° of the magnetic equator. The high latitude region extends poleward from about ~60° geomagnetic, and the mid-latitude is between these two regions. The high latitude ionosphere can be further sub-divided into two; which are the auroral region (approximately ~60° to ~70° magnetic) and the polar cap (from the auroral region poleward). The TEC variations in the equatorial and polar region are known to be high compared to moderate changes in the middle latitude region (Panda, Gedam, & Rajaram, 2015). Furthermore, TEC is highly variable and it changes with geographic and geomagnetic location, solar activity, time of day, seasons, and magnetic disturbances.

Therefore, this study aims at finding the relation of TEC variations between equatorial and polar region, and how the solar activities, diurnal, seasonal, and geomagnetic conditions affect the ionospheric TEC variations over these regions.

1.2 Problem statement

The research area in TEC variations has led to more specific and detail investigation because of the structure and feature of the ionosphere are constantly varying. The ionosphere is varied due to its temporal and spatial behaviors substantially in the equatorial and polar region. The ionosphere behavior acts differently in each equatorial and polar ionosphere.

Both equatorial and polar ionospheres are subjected to a larger scale of normal and unexpected ionospheric behavior and one of the main causes is the Earth's magnetic field. In the polar region, the magnetic field lines are almost perpendicular to the Earth's surface or in the vertical direction, while in the equatorial region, the magnetic field lines are horizontal to the Earth's surface at the magnetic equator. These charged particles of magnetic field lines cause variation in the ionosphere electrons. Therefore, the difference in the movement of Earth's magnetic field around the equator and polar region can cause difference variations of TEC in respective regions. Investigation on ionospheric TEC at individual regions has been carried out by many studies but the investigation between these regions simultaneously is still lacking.

Referring to past investigation carried out by (Guo *et al.*, 2015), the authors estimate the global TEC data from 1999 to 2013 by processing the GPS data collected by the IGS stations, and robustly constructed the TEC time series at each of the global 5°×2.5° grids. The time resolution of 2 hours from 1999 to 2013 and the height of maximum electron density above 500 km might be the factors of their findings where the amount of TEC at the equator is three times greater than at the high latitudes. This investigation is carried out by using global spatial TEC distribution instead of focusing TEC variations on the specific geographic and geomagnetic location which is one of the main circumstances to be followed in order to achieve the aim of this study.

The aim of this study is to investigate the relation of TEC variations between equatorial and polar stations simultaneously by determining the rate of TEC changes. It investigates the relation of TEC between the equator and polar stations for the years 2009, 2011, and 2013 to obtain precise comparison of TEC values. It will focus on the rate of TEC changes for 1 hour time interval for each particular year.

1.3 Objectives of study

Based on the problem statement discussed in the previous section, the objectives of this study are:

1. To investigate the behavior of ionospheric parameters, in particular, TEC, over the equatorial and polar stations due to different solar activity at solar cycle 24.
2. To analyze the TEC behavior under several conditions such as different solar and geomagnetic activities, and diurnal and seasonal variations.
3. To relate the TEC variations between the equator and polar stations simultaneously.

1.4 Scope of study

This study focuses on the relationship of TEC variations between the equator and polar stations. A study in TEC variations between different regions is set to be the most significant investigation because of their different magnetic field movement, and temporal and spatial behaviors. Raw data from GPS-based measurement provided by the International GNSS Service (IGS) server are used. MATLAB is used to compute TEC values. The two stations are selected which are Libreville (*NKLG*), Gabon (0.354° N, 9.672°E) and Ny-Alesund (*NYA1*), Norway (78.929° N, 11.865° E), each representing equatorial and polar stations. The selected years are 2009, 2011, and 2013 to differentiate between low, medium, and high solar activity level.

1.5 Significance of study

TEC is a very important parameter to investigate the characteristics of ionospheric behaviors. To some extent, with the TEC behaviors analysis, one can develop ideas to construct more stabilized and reliable developing modern communication technology that best suited for complex ionospheric disturbance events, particularly at the equatorial and polar region.

These changes in the ionosphere affect navigation systems, surveillance systems, and modern technologies as well such as communication systems since the signal from the satellite to the receiver must pass through the ionized layer. As a consequence, a good description of the ionosphere is needed in order to observe the changes in the ionosphere and predicting the effect of the space weather conditions at these regions.

This study might lead to constructing an automated forecasting TEC model. This automated system will apply the rate of TEC changes into the TEC model.

1.6 Thesis outline

This thesis consists of five chapters. Chapter 1 presents a general description of GPS, the ionosphere, TEC and its variations at each equator and polar region under several conditions. This chapter also explains the problem found in previous work comparing with this study, the objectives of this study, and the significance to carry out this work.

Chapter 2 explains the background of the ionosphere, TEC measurements, and instrumentation including GNSS, solar cycle 24, the geophysical phenomena that can affect TEC variations, the TEC behavior under diurnal, seasonal, geomagnetic storm conditions, and the previous work of finding the relation of TEC between the equator and polar region.

Chapter 3 describes the process carried out to obtain the TEC values and to analyze TEC under several conditions. This chapter explains data exchanges format files involved in order to be processed by MATLAB then later to compute TEC values. This chapter also shows the calculation of averaged TEC used to analyze its variations.

Chapter 4 presents and discusses the findings of final VTEC at *NKLG* and *NYA1* stations under diurnal, seasonal, and geomagnetic variations in 2009, 2011, and 2013. This chapter also shows the main findings of a study which is the relation of TEC variations between stations by using the rate of TEC changes.

The end part of this report consists of Chapter 5 which concludes the whole report and suggests few future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The quality of GPS signals transmitted from the transmitter to the receiver depends on the electron content in the ionosphere. The propagated signals from the satellite to the receiver's location are refracted due to the density of electrons in the ionosphere. The density of electrons is formed by the morphology of the ionosphere layers. This temporal and spatial features of ionosphere due to the electron variations which can be categorized by factors such as solar activity, diurnal, seasonal, and geomagnetic variations. The ionospheric TEC behavior is different in each equatorial and polar region. The natural phenomenon is one of the main causes to influence the TEC variations in both regions.

2.2 The ionosphere

The Earth's atmosphere consists of four predominant layers that are the troposphere, stratosphere, mesosphere, and thermosphere. These layers are very important to human and livings on the Earth as they absorb harmful radiation from ultraviolet sunlight. It controls the amount of temperature around the Earth and maintains stable temperature structure to prevent the harmful effects of excessive exposure to the UV radiation. Figure 2.1 shows the Earth's atmospheric layers.

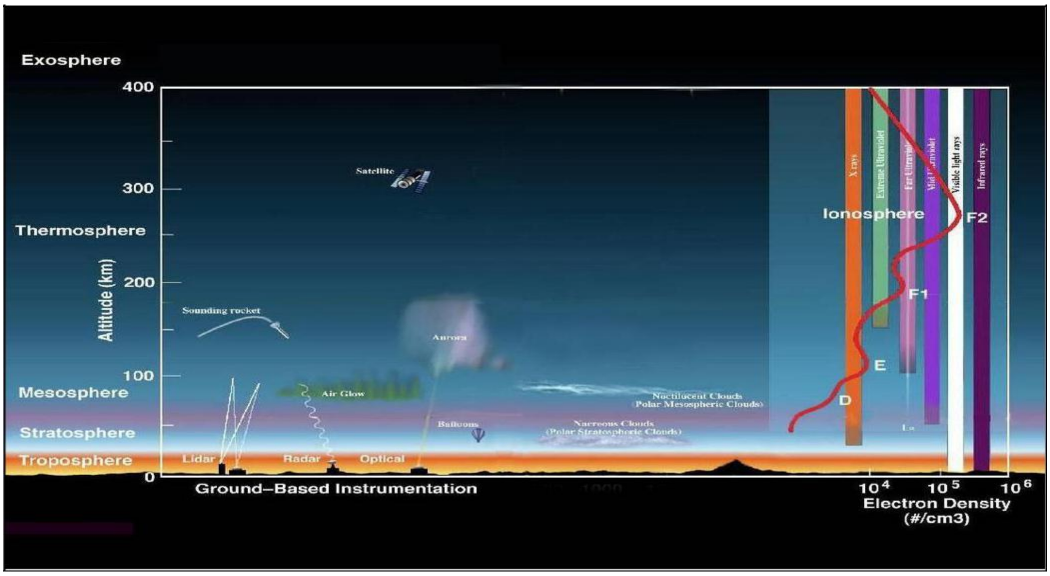

Figure 2.1: Earth's atmospheric layers (National Aeronautics and Space Administration, Nov 2013)

Moreover, concerning the communication of radio system on the Earth, ionosphere takes place as the medium of communication and radio signals propagation. The ionosphere is a copious layer of electrons and ionized atoms and molecules that extends approximately from 50 km above the surface of Earth's ground to the extremity of space at about 1000 km in which overlapping into mesosphere and thermosphere. The ionosphere is a layer of plasma formed by the ionization of atomic and nitrogen. The ionization process occurred because of solar radiation. The main property of the ionosphere that helps radio signals propagation over a long distance is that it can reflect radio signals. Ionized ionosphere layer bounce signals off to the receiver. However, the reflected signals may have errors caused by some incidents such as diffraction, polarization, absorption, and other interferences. As for GPS, the signals efficiency can be improved by reducing the errors found.

Ionized ionosphere layer consists of charged particles that affect radio signals propagation. The investigation on the behavior of radio signals in the ionosphere that has been carried out by previous researchers implies that the radio signals propagation occurs by reflecting signals in the ionosphere (Grima, Blankenship, & Schroeder, 2015). Therefore, the ionosphere simply plays an important region in the matter of communication and radio navigation system around the world.

2.3 Formation of ionosphere

2.3.1 Ionization and recombination process

Foremost, the Sun itself has high intensity of energy particles. The particles capable of breaking an atom or a molecule bond moving in the atmosphere (MacDonald, 2015). The Sun emits vast quantities of radiation of all wavelengths and travels towards the Earth. Ionization takes place when the radiation hits atoms or molecules in Earth's atmosphere and producing free electrons. Atoms and molecules consist of electrons, protons, and nucleus. The high energy particles from the radiation break down bonds of electrons from atoms or molecules considered as excess kinetic energy. It causes the negative and positive ions separating, and these the negative ions are also known as free electrons.

However, as the radiation travels down to the lower altitude of the ionosphere, the radiation intensity becomes weaker thereby slowing down the ionization process. The density of the electrons also varies as the ionization varies. It infers that electron density is much higher at high altitude of ionosphere due to the Sun radiation is extremely high at this altitude. Ionization produces free electrons during the daytime and the reverse process occur during the nighttime called the recombination process. It means that the opposite charges of positive and negative ions pulled towards one another and they might combine. It happens because the Sun radiation intensity is extremely low particularly at night caused by slow ionization process (MacDonald, 2015). This has a significant effect on the communication and radio navigation system.

2.3.2 Ionosphere layers

The distinct level of ionization process in the ionosphere is formed into three primary layers within the ionosphere and signal communication is affected in different ways. They are the D layer, E layer, and F layer (Leick, Rapoport, & Tatarnikov, 2015). The diagram of these layers is shown in Figure 2.2. However, the F layer is divided into F_1 and F_2.

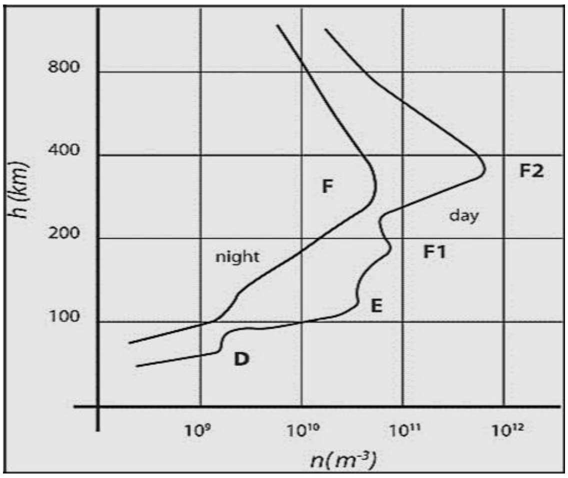

Figure 2.2: The ionosphere layers (Leick *et al.*, 2015)

h is the height of altitude from sea surface and *n* is the electron density in unit m^3. The D layer is the lowest region within the ionosphere. It is located at altitudes of about 60 to 90 km and the radiation reaches this layer only during daytime to an extent that affects radio signals propagation perceptibly. The level of ionization decreases speedily at dawn when the Sun radiation is extremely low and the recombination process takes place at the time. It can only reflect radio signals particularly in low and medium frequencies of the radio wavelength spectrum. The effect on this is less appearing in reducing the frequency, especially during nighttime though there is still a sufficient level of ionization for it to reflect very low-frequency signals. However, the received GPS signals are very weak.

The E layer is above the D layer at about 100 to 125 km. The behavior of radio signals propagating in E layer is a reflecting signal in a slightly bigger amount than that of D layer and the ionization in the E layer decreases speedily at dawn. The lower part of the E layer can attenuate lower portions of the high-frequency part of the radio wavelength spectrum.

The F layer is the most important region in the ionosphere for long distance high-frequency radio signals. During daytime, the F layer splits into two sub-regions that are the lower region of F_1, and the higher region of F_2. The F_1 layer appears at around an altitude of 300 km while the F_2 layer appears at around an altitude of 350 km. The density of free electrons at the F layer is the highest and varies the most. However, the level of ionization in the F layer also drops at dawn when the recombination process starts to appear. Despite that, the level of ionization at night remains very much higher than those other lower regions. (Paul *et al.*, 2016)

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